Development of a Synchronous-Generator Experimental Bench for Standstill Time-Domain Tests

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ABSTRACT

This paper presents the development of an experimental bench for performing time-domain tests on synchronous machines at standstill. The test bench allows the collection of experimental data which can then be used in the parameter estimation of mathematical models of synchronous motors and generators. The system development is based on the LabVIEW programming language. It effortlessly allows the calibration of voltage and current sensors, the *d-q* magnetic axis positioning of the synchronous generator, and the spectral analysis from the collected data. In addition, the testing environment includes non-sophisticated instrumentation elements and a power amplifier. This experimental bench has a friendly user interface which guides the user throughout a defined methodology to allow the achievement of the different time domain tests on synchronous machines. A 7kVA, 220V, 60Hz synchronous generator was used to show the functionality and usefulness of the test bench in research and teaching electrical machine theory.

Keywords: Synchronous generator, time-domain tests, standstill tests, virtual instrument.

RESUMEN

Este artículo presenta el desarrollo una plataforma para implementar pruebas experimentales en el dominio del tiempo a generadores síncronos en estado de reposo. La plataforma de pruebas permite la obtención de datos experimentales que pueden ser utilizados posteriormente para la estimación de parámetros tanto de los modelos matemáticos de motores como de generadores síncronos. El desarrollo del sistema se basa en el lenguaje de programación LabVIEW, permitiendo de manera sencilla la calibración de los sensores de corriente y de voltaje, el posicionamiento de la máquina síncrona en sus ejes *d-q*, así como el análisis espectral de las señales adquiridas. Además, el sistema cuenta con elementos de instrumentación no sofisticados y un amplificador de potencia. La plataforma incluye una interfaz amigable que guía al usuario a través de una metodología definida del desarrollo de las diferentes pruebas en el dominio del tiempo en generadores síncronos. Para demostrar la funcionalidad y utilidad de la plataforma de pruebas en la enseñanza e investigación de máquinas eléctricas se empleó un generador síncrono de 7kVA, 220V y 60Hz.

1. Introduction

Synchronous generators are important components within an electrical network because they are the main source of electrical energy generation. The modeling of synchronous generators has been the subject of many investigations over the years due to their following roles in a power system: a) a power analyst requires mathematical models to predict the machine performance under normal and abnormal conditions, and b) the control engineers also need the generator models and their parameters to design the automatic voltage regulators of the synchronous generators. The parameter estimation process is usually carried out by testing the electrical machines either online or at standstill. The measured data are then employed in the fitting of a predefined model structure. Therefore, it is important to have a versatile experimental bench for performing tests and collecting data in the research of machine modeling and parameter identification. Experiments to obtain synchronous machines parameters may broadly be classified in two groups: frequency domain and time-domain tests [1], [2], [3]. Some of these tests are performed while the machine is online and others when it is offline. Online tests are executed when the generators are in normal operation and these tests are normally forbidden because of the possibility of damage or due to economical reasons (energy loss by generator tripping). Meanwhile, offline or standstill time-domain tests are nondestructive tests because the machine is offline and they can rapidly be performed. Hence they have attracted the attention of researches due to their simplicity and easy implementation. [4], [5], [6], [7].

Experimental data are commonly used in other engineering areas where data are essentially used to validate mathematical models. Some examples of data application have been reported in power electronics and in chemical engineering [8], [9]. Educational virtual instruments programmed in the LabVIEW software can be found in [10], [11],[12]. Testing environments have also been reported in other areas like microelectronics and oceanographic [13], [14]. In these cases, the data quality (low signal noise) is an important feature to be taken into account because it depends on the employed hardware and instrumentation. The fast development in computer technology and the availability of high level programming languages have allowed the data acquisition and signal generation throughout acquisition cards.

In this paper, the design and development of a novel experimental bench for performing standstill time-domain tests to a synchronous generator is presented. Hardware and software are the two main components of the test bench which have the objectives of generating and collecting all experimental data needed in the identification process of a synchronous generator. A virtual instrument was designed and developed to generate a set of time-domain signals and to acquire the voltages and currents of the generator. A power amplifier was developed to have the proper voltage level needed in the excitation of the generator windings. The test bench is capable of carrying out the sensor calibration, magnetic axis positioning, signal filtering and spectral analysis. The data delivered by the experimental bench can be applied to the identification of two-axis mathematical models of synchronous generators. Finally, it is relevant to point out that there is not similar equipment in the market. Hence, this test bench will allow the research of electrical machine modeling considering time-domain tests. A 7 kVA, salient pole, 60 Hz, 220 V synchronous machine is employed to illustrate the applicability of the proposed testing environment.

2. Synchronous generator standstill tests

The current advances in computing tools have allowed the detailed modeling of synchronous generators. They are normally constructed by a field or dc excitation winding located on the rotor and a three-phase winding found on the stator. A detailed synchronous machine model considers the effect of other components such as laminated or solid rotors and pole-face damper windings, which play an important role during transient periods when eddy currents are induced in damper windings. Models structures are normally based on the Park transformation which changes a three-phase rotating system into a two-phase stationary system. As a result of applying the Park transformation, it is possible to have a set of equations that describes the dynamics of synchronous generators in terms of the equivalent circuits. To estimate the inductances and resistances of the generator model, it is necessary to have experimental data and then carry out the parameter estimation. The tests normally performed to the synchronous generators are online and standstill. Standstill tests are performed while the synchronous generator is disconnected from the power system. Many of these tests for extracting synchronous generators parameters have been proposed; some of them are included in specialized standards. The dc step voltage and dc decay tests have been successfully employed to obtain synchronous generators parameters even though they are not found in standards [4], [5]. Alternatively, special time-domain signals offer an alternative to be applied as an excitation signal since they excite a wide range of frequency components [15], [16]. In the test bench presented in this work, the following time-domain signals are applied to the synchronous machine while at standstill: cardinal sine *(sinc),* chirp, voltage pulse, dc decay, and dc step voltage.

3. Generator test bench

Parameter estimation of synchronous generator models requires of an experimental bench to perform the most common test procedures at standstill and to produce the data needed in the estimation. One of the most useful features of the proposed test bench is its friendly graphical interface developed on the LabVIEW language program, which allows an easier application of the time-domain test to the generator. In addition, the user can perform the following required tasks in the experiment: d-q axis rotor positioning, sensor calibration and spectral analysis by means of the *FFT* as shown in Figure 1. In order to develop the tasks shown in Figure 1, different hardware configurations are required. A detailed explanation of the proposed testing environment is presented in the following subsections.

3.1 Sensor Calibration

The quality of the estimated parameters of the generator depends on the accuracy of measurements. For this reason, a virtual instrument was developed to carry out the sensor calibration. The calibration set up is presented in Figure 2 where the schematic diagram of the generator, the power amplifier, acquisition card and a personal computer that runs the virtual instruments can be seen. A dc signal generated by a virtual instrument (Figure 3) is fed into the power amplifier which excites two phases (*b-c*). The power amplifier was developed by using bipolar transistors in push pull configuration (MJ2193G and MJ21194G), and these transistors are driven by a high-voltage linear amplifier (OPA445). Current and voltage measurements are taken using calibrated meters (Fluke 87V/E2) and written into the virtual instrument at each excitation. At the same time, the stator current (i_{bc}) is sensed by a Hall Effect sensor (LEM LTS06-NP) and it is acquired by a data acquisition card. Due to the low stator resistance, it was not necessary to use a voltage sensor, therefore the voltage (v_{bc}) was directly measured while the generator field winding is short circuited. The acquired data are then employed in order to characterize the response of the Hall effect sensors.

The measurements are taken at different dc current levels given by the dc level dial located in the front panel; a mean value of these measurements was also computed by the virtual instrument. These values are saved in a text file and they are subsequently employed to fit a linear equation. The resulting linear equation is also saved into a text file. The stator and the field winding sensor calibration are made separately from each other to separate the magnetic effects. The field sensor calibration is carried out in a similar way as that of the stator with the difference that a dc voltage is applied to the field winding.

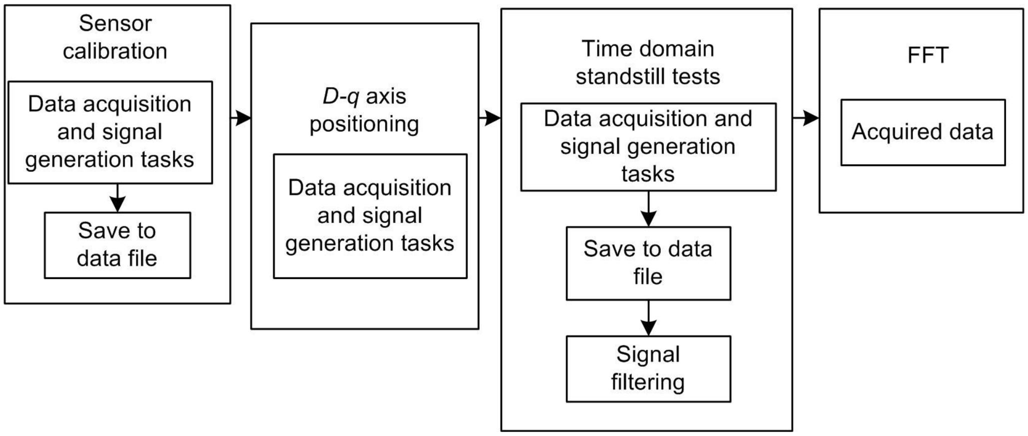


Figure 1. Block diagram of the experimental bench.

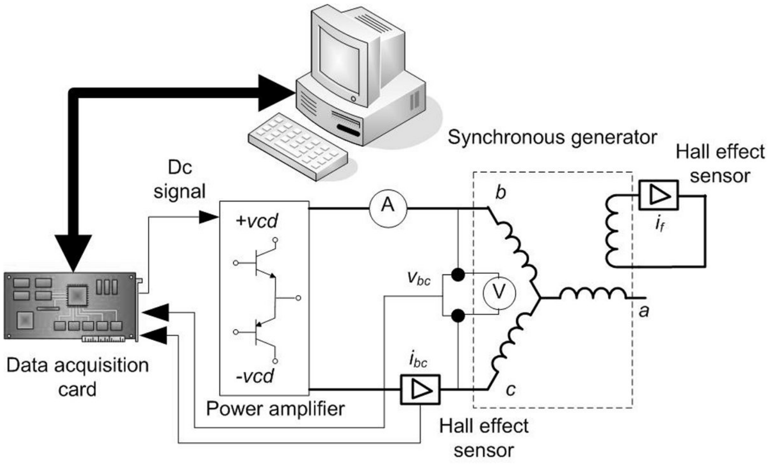
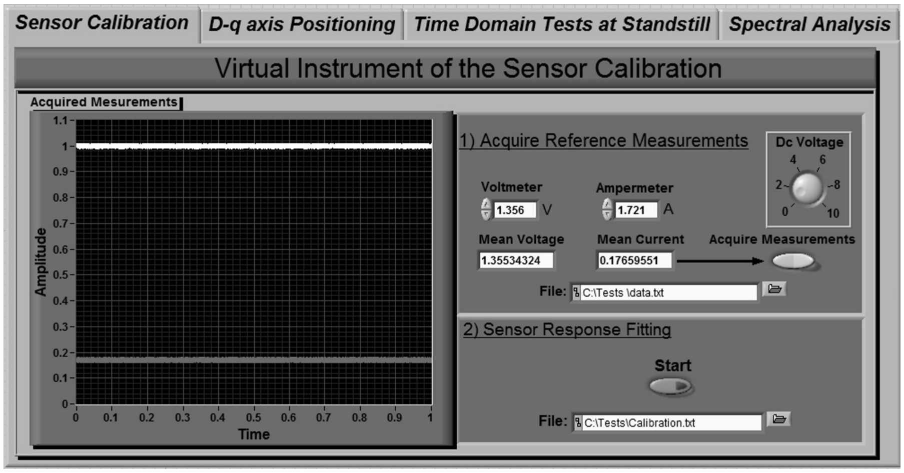


Figure 2. Experimental setup for the stator sensor calibration.



Voltmeter: 1.356 V

Ampermeter: 1.721 A

Dc Voltage: 0 2 4 6 8 10

Mean Voltage: 1.35534324

Mean Current: 0.17659551

File: C:\Tests \data.txt

File: C:\Tests\Calibration.txt

Figure 3. Virtual instrument for the sensor calibration.

3.2 D-q Axis Synchronous Machine Positioning

In order to carry out the proposed standstill time-domain tests, firstly, the rotor has to be positioned as to get its *d* or *q* magnetic axis because the objective of this test bench is to collect data for estimating parameters of two-axis models.

The two-axis modeling theory is based on the Park transformation, which is given by (1) and (2), and it transforms a three-phase system into a decoupled two-axis one.

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta - \frac{4\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{4\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta - \frac{4\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{4\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{2}$$

where v and i stand for voltage and current, subscripts d, q and 0 represent the d-axis, the q-axis and zero sequence values, respectively. Subscripts a,b,c represent stator phases and s is the stator. Angle θ is the rotor angular position.

The two-axis theory eliminates rotor-position dependence of some inductances making the generator model easier to handle. The experiment setup employed to carry out the d-axis positioning is based on the reference [2] and it is shown in Figure 4. A power amplifier is connected through the *b-c* and *a* phases and it is driven by the virtual instrument that generates a 100 Hz sinusoidal signal. The induced field voltage (v_f) is monitored by the Hall effect sensor LEM LV25-P while the rotor is slowly rotated until the induced field voltage has a null value. At this position, the magnetic axis of the field winding is aligned with the axis of phases *b-c* and *a* that defines the direct axis of the synchronous generator. On the other hand, the q-axis positioning is carried out using the d-axis positioning procedure explained before; where the connection between phases b and c is eliminated. In other words, phases b and c are separately connected to the power amplifier terminals, while phase a is disconnected. The d-axis voltage and current are obtained by applying the two axis transformation given by (1) and (2) and taking into account that the angle between the a phase and field winding is 90 degrees which leads to (3)-(6), where it is seen that the d-axis quantities are decoupled from the q-axis and zero sequence components [15].

$$v_d = -\frac{v_s}{\sqrt{3}} \tag{3}$$

$$i_d = \frac{2}{\sqrt{3}} i_s \tag{4}$$

$$v_q = i_q = i_0 = v_0 = 0 \tag{5}$$

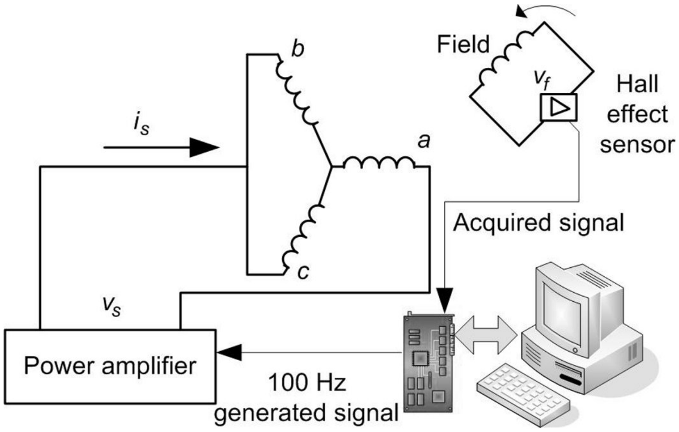


Figure 4. *D*-axis rotor positioning.

The expressions for the *q*-axis voltage and current are derived by considering that the angle between the *a* phase and field winding is zero degrees, which gives Equations (6)-(8), where it is seen that only *q*-axis components are obtained and the *d*-axis and zero sequence quantities are cancelled out.

$$v_q = -\frac{1}{\sqrt{3}} v_s \tag{6}$$

$$i_q = \frac{2}{\sqrt{3}} i_s \tag{7}$$

$$v_d = i_d = i_0 = v_0 = 0 \tag{8}$$

3.3 Virtual Instrument for the Generation of Excitation Signals.

A virtual instrument (VI) was designed to generate the excitation signals: cardinal sine (*sinc*), *chirp*, voltage pulse, dc decay and step voltage, which are applied in the generator standstill tests. The signal generation and data acquisition was performed with a sampling of 10 kS/s. The VI also contains panel controls which allow choosing the time domain signal with their parameters, i.e. sampling frequency and signal amplitude. The generator responses i_s, i_f and v_{bc} are plotted and saved in a text file which will be employed to compute a spectral analysis of the measurements. To carry out the standstill tests two different experiment configurations are considered. The dc decay and step voltage tests need mercury relays and a dc power source. On the other hand, *sinc*, *chirp* and voltage pulse signals use a power amplifier to reach high excitation levels. The test bench employed to execute the dc decay and step voltage tests is shown in Figure 5.

It is necessary to emphasize the importance of using mercury relays (Figure 5d) because they avoid the bouncing normally present at their activation time. This bouncing can affect the response signals, in the sense of giving erroneous dynamics and hence bad parameter estimates. For the dc decay and step voltage tests a digital signal which comes from the PC (Figure 5a) is fed into the driver circuit (Figure 5b) which enables two mercury relays (Figure 5d). In addition, a dc power supply

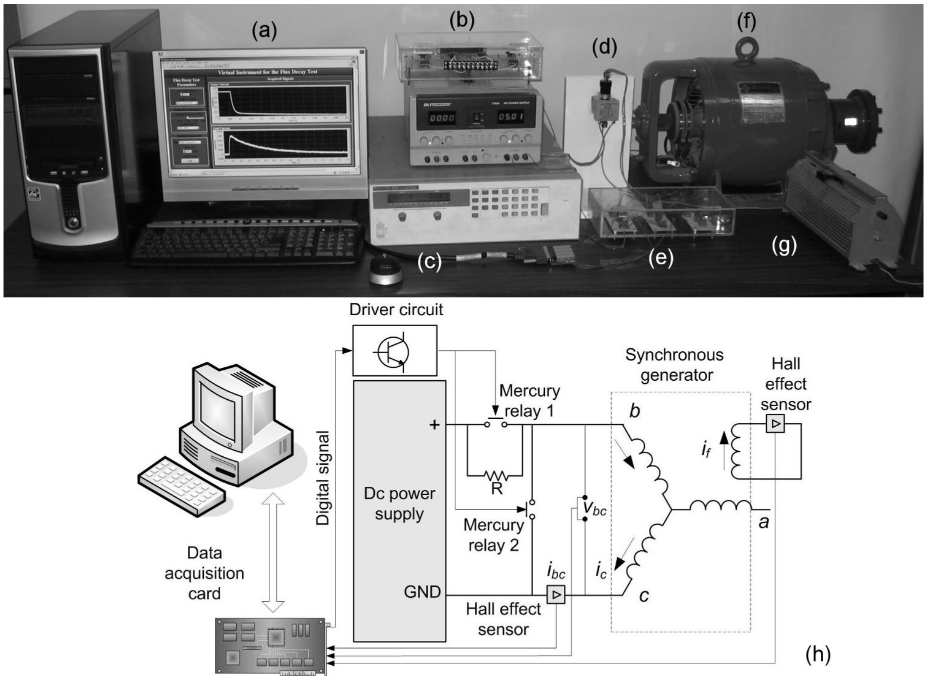


Figure 5. Test bench for the dc decay and step voltage tests. (a) PC, (b) driver circuit, (c) DC source, (d) mercury relays, (e) Hall effect sensors, (f) generator, (g) resistance, (h) schematic diagram for step and decay tests.

(Figure 5c), in series with a resistor (Figure 5g), feeds the synchronous generator (Figure 5f). In the application the dc decay test, a mercury relay (relay 1) connected in parallel with the stator phases is used and another relay (mercury relay 2) connected in series with the stator winding remains closed (Figure 5h). This connection allows a current flow through the stator winding while the field winding is short circuited. When the test is triggered, the mercury relay connected in parallel is closed and a decay flux will be present on the stator; and an induced voltage will be present on the field winding which is caused by the sudden change on the stator current. On the other hand, the step voltage test is performed similarly as the dc decay test with the difference of suddenly closing the mercury relay connected in series with the stator. The above stated is illustrated in Figure 5h where schematic diagrams for the step and decay tests are presented. The *sinc*, *chirp* and voltage pulse tests are more easily performed than the dc decay and step voltage tests because they are not programmed as additional tasks. After the standstill tests have been concluded, a zero-phase filter is automatically executed offline to eliminate undesired noise of the acquired data. The experiment procedures described above are also executed for the *q-axis*.

3.4 Virtual Instrument of the Spectral Analysis

The virtual instrument for the spectral analysis represents the last element in this test bench, and it is shown in Figure 6. In this part, the acquired responses are read in from text files, they are plotted and their spectrum is calculated by means of the Fast Fourier Transform (*FFT*). In this front panel, the user can choose the desired time-domain signal applied to the synchronous generator while it is at standstill. This embedded tool allows the user to see the frequency bandwidth of the time-domain excitation signals.

4. Experimental results

In the five time-domain signals applied to the generator, the amplitude is adjusted to obtain 1A approximately, which represents 5.4% of the rated current. It is worth mentioning that the suggested value of 0.05% was not employed for the frequency response tests as indicated in [2], because it implies an excitation current of 9 mA in the stator which is difficult to measure because it is a noisy and small field current. The applied *d*-axis generator voltage signals for the *sinc*, *chirp*, *step*, decay and pulse tests are shown in Figure 7. It can be seen that the step voltage is not an ideal step

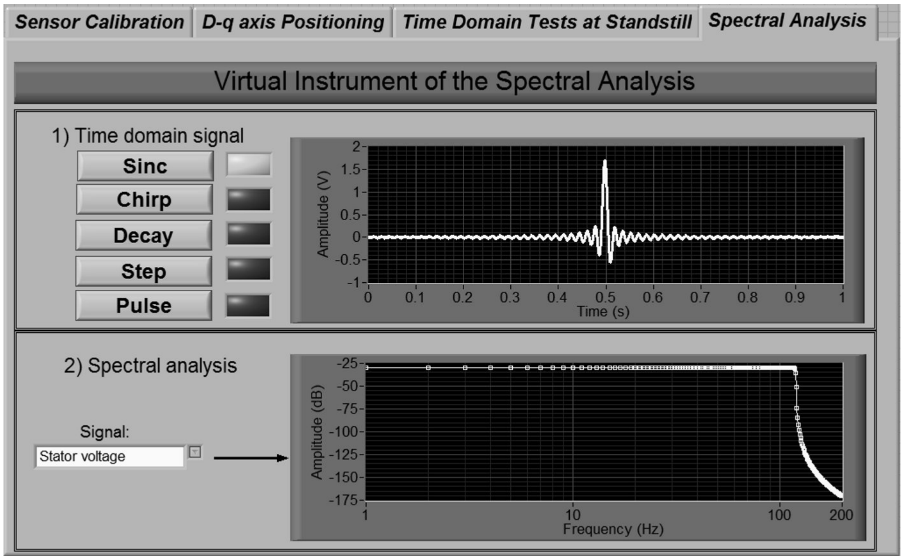


Figure 6. Virtual instrument for the spectral analysis.

$$V_{sinc} = \begin{cases} V_m & t = t_{delay} \\ V_m \dfrac{\sin\left(2\pi f_{\text{sinc}}\left(t - t_{delay}\right)\right)}{2\pi f_{\text{sinc}}\left(t - t_{delay}\right)} & t \neq t_{delay} \end{cases} \tag{9}$$

$$V_{pulse} = \begin{cases} V_m \sin^2\left(2\pi f_{pulse} \quad t + \varphi\right) & \textit{for} \ \ t_{start} < t < \left(t_{end} + t_{pulse}\right) \\ 0 & \textit{for} \ \ t_{start} \geq t \geq \left(t_{end} + t_{pulse}\right) \end{cases} \tag{10}$$

signal because the dc power supply is not robust enough to keep the voltage regulated during the step transient. The cardinal sine presents asymmetrical negative peaks because of the dynamic response of the electronic amplifier with inductive loads. The expressions for the sine cardinal (V_{sinc}) and voltage pulse (V_{pulse}) signals are given by (9) and (10), respectively.

where V_m is the maximum signal amplitude, t is the time in seconds, t_{delay} is the time where the maximum occurs, f_{sinc} is the sine cardinal frequency, f_{pulse} is the frequency of voltage pulse, φ is the phase shift angle, t_{start} and t_{end} are the initial and final times of the pulse.

The spectral analysis for the applied time-domain signals on the *d*-axis is shown in Figure 8. In this figure, the range of frequencies that are excited during each test can be appreciated.

The spectrum of the dc decay and step voltage shows that the harmonic magnitudes are similar and they have a constant value until 10 Hz , and afterwards they start decreasing at a low rate. The pulse voltage harmonic behavior is better in the sense that amplitude is almost constant below the frequency of interest (120Hz). The *chirp* test shows the greatest variation of amplitude of all signals within the frequency bandwidth of interest. Finally, it is seen that the *sinc* test is the better, because it has harmonics of constant amplitude below 120Hz. On the other hand, the harmonic contents for the currents of the stator and field windings while the generator is at standstill with the cardinal sine perturbation are shown in Figure 9, where it can be seen that the amplitude of the harmonics has an almost constant value for the bandwidth of interest. The field current spectrum gives harmonics with smaller amplitudes, because the field current has a small induced value. At higher frequencies than 120Hz, the spectrum of the experimental measurement exhibits noise, therefore it can be discarded for any analysis.

The ultimate objective of the collected data in this testbed can be used to estimate the parameters (inductances and resistances) of the *d*-*q* axis equivalent circuits of the synchronous generator. The estimation may be carried out by using estimation algorithms, i.e. the least squares method or novel algorithms, and optimization methods (deterministic or stochastic) which will yield the unknown set of parameters. Alternatively, the time constants and machine reactances can be derived graphically by employing the same collected data, although this method is seldom used. Although the testbed has been developed for synchronous machines, it can be used in other types such as induction, direct current and permanent magnet machines, where the collected data can be used in the parameter identification of two-axis models. This testbed cannot be applied to large generators because of the limited capacity of the power amplifier and mercury relays. In order to be used in the characterization of large power machines, the amplifiers and relays need to be redesigned.

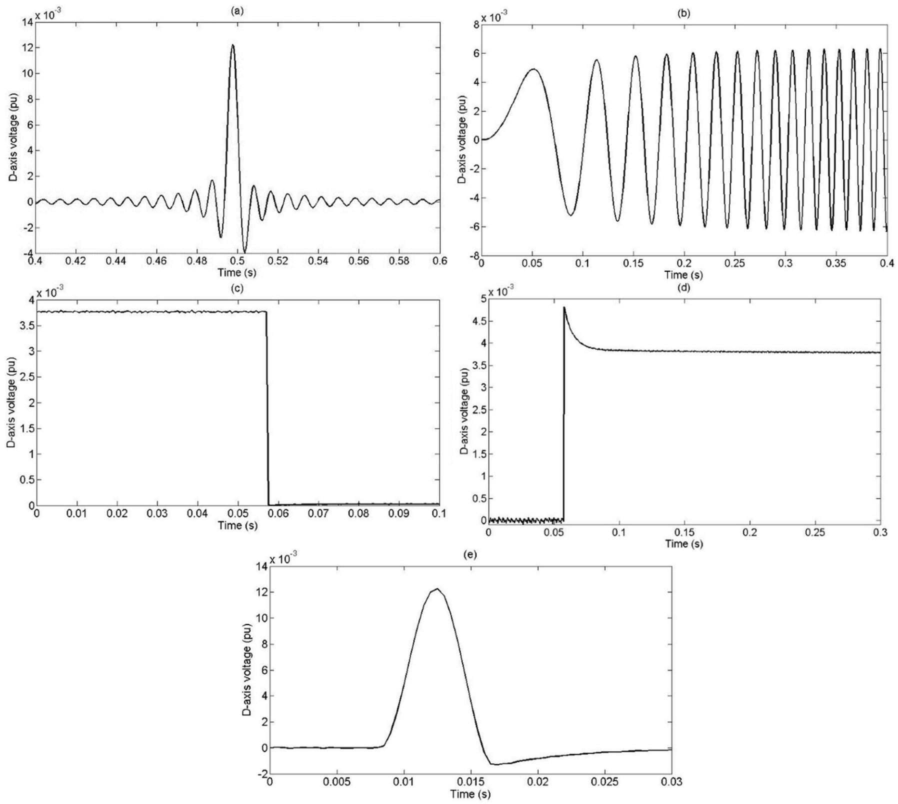


Figure 7. Experimental excitation signals used at standstill tests: a) sinc signal, (b) chirp signal, (c) decay signal, (d) step signal, (e) voltage pulse signal.

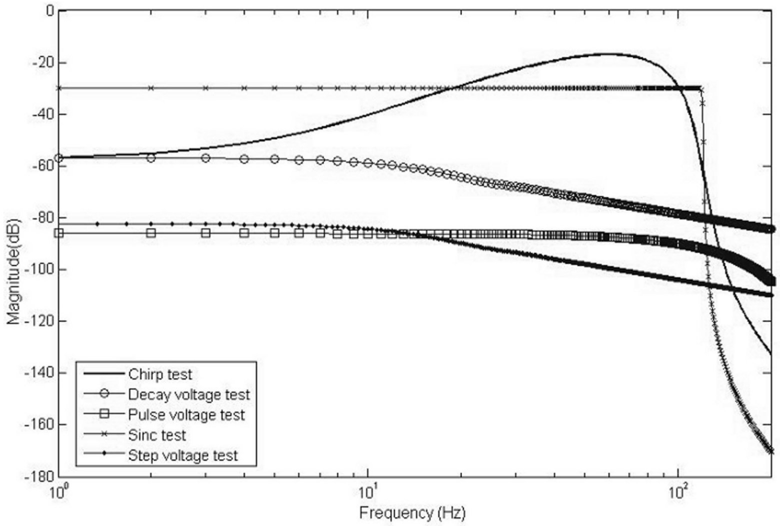


Figure 8. *D*-axis spectral analysis for the applied voltage of the signals.

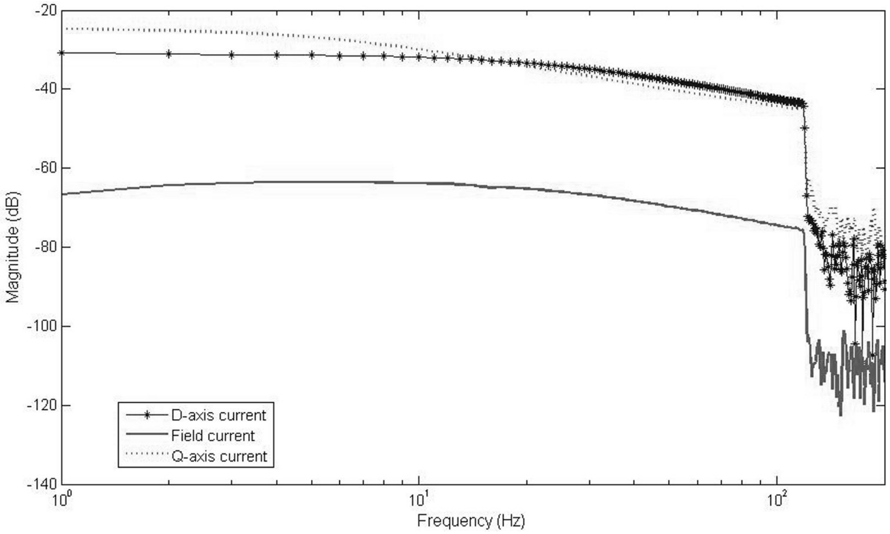


Figure 9. Spectral analysis for the *d*-axis, q-axis and field currents with the sinc excitation.

5. Conclusions

In the process of parameter estimation of synchronous generator models it is very important to have reliable experimental data. In this paper the development of a test bench was presented. A detailed description of its elements was given, namely, a virtual instrument, a power amplifier, dc power supply, Hall effect sensors and mercury relays. One of the most remarkable system advantages is the use of virtual instruments where its friendly user interfaces allow an easy test execution. The ability of an experimental bench to guide non-expertise as well as expertise users throughout the process of the standstill time-domain tests is demonstrated. The test bench was successfully applied to a synchronous generator of 7kVA, salient poles, 60Hz, 1800 rpm. Moreover, it was demonstrated to be useful for teaching or researching purposes and its use can be extended to other types of electrical machines with minimal modifications to the testing platform.

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